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Dynamic force microscopy at high cantilever resonance frequencies using heterodyne optical beam deflection method

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We have developed a dynamic force microscope (DFM) with a wideband cantilever deflection sensor using heterodyne optical beam deflection (HOBD) method. The bandwidth of HOBD method is limited only by the maximum frequency for laser power modulation, which can be as high as gigahertz order. This technique allows us to use high cantilever resonance frequencies for improving the sensitivity and time response of DFM. In this letter, basic principle and experimental setup of HOBD method are described. Deflection measurement of a cantilever vibration at about 7 MHz is demonstrated. Using this cantilever, DFM imaging with a relatively fast scanning speed is performed. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1842368]

Dynamic force microscopy (DFM)[1] allows us to visualize subnanometer-scale structures on various surfaces.[2,3] DFM-based techniques have also been used for the local surface property measurements with a nanometer-scale resolution.[4] The force sensitivity and time response of DFM are essential factors to determine the performance of these DFM-based techniques. In addition, high force sensitivity and fast time response of force detection make possible high-speed and high-resolution imaging, which opens a wide variety of new applications such as real-time imaging of dynamic behavior of biological samples.[5]

The force sensitivity and time response in DFM can be improved by increasing cantilever resonance frequency.[1,6] The same is true of various surface property measurements using DFM.[7] For example, Kelvin probe force microscopy (KFM) using the second resonance frequency of a cantilever[8] shows a better time response and a higher force sensitivity than conventional KFM using an off-resonance frequency.[7] However, the bandwidth of the cantilever deflection measurement systems used in conventional DFM setups is mostly limited to less than about 1 MHz, which prevents us from using higher cantilever resonance frequencies in DFM experiments.

Recently, Dupas *et al.*[9] have presented a way to overcome the frequency limitations of the cantilever deflection measurement systems, which is hereafter referred to as heterodyne optical beam deflection (HOBD) method. The method has enabled wideband deflection measurements with small modifications from the experimental setup for conventional optical beam deflection (OBD) method. They have investigated local mechanical properties at a certain position by measuring the vibration spectra of a cantilever in contact mode including higher modes of the resonance.[9] In spite of a wide variety of potential applications of HOBD method, its applications to any other techniques have not yet been reported. In this letter, we first present applications of HOBD method to DFM measurements. The basic principle and experimental setup of DFM using HOBD method are described. Deflection measurement of a cantilever vibration at about 7 MHz is demonstrated. Using this cantilever, we performed DFM imaging with a relatively fast scanning speed.

Figure 1 shows an experimental setup of DFM using HOBD method. The setup for HOBD method is basically the same as the one used for conventional OBD method. The only difference is that the laser power used in HOBD method is modulated at a frequency (ω_m) close to the cantilever vibration frequency (ω_0). In this way, the photocurrent induced by the bounced laser beam changes in proportion to both cantilever deflection and the laser power variation. Thus, the output signal of the preamplifier contains a beat signal with a frequency of $\omega_0-\omega_m$. If the frequency $|\omega_0-\omega_m|$ is less than the bandwidth of the photodetector (B), the amplitude, frequency and phase of the cantilever vibration can be measured by detecting the ($\omega_0-\omega_m$) component even when ω_0 is much higher than B. The bandwidth of HOBD method is limited only by the maximum frequency for laser power modulation, which can be as high as gigahertz order.[10] The method can be easily applied to most of the DFM applica-

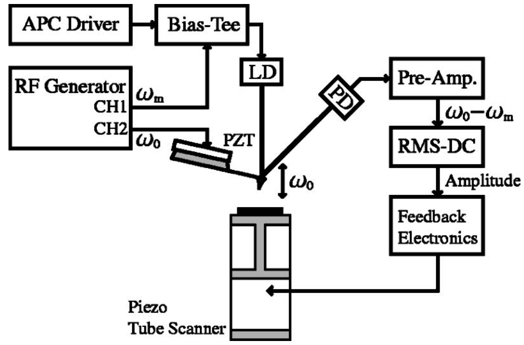

FIG. 1. Experimental setup of DFM using HOBD method. The laser power is modulated with a frequency ω_m so that the output signal of the photodetector contains the beat signal with a frequency of $\omega_0-\omega_m$.

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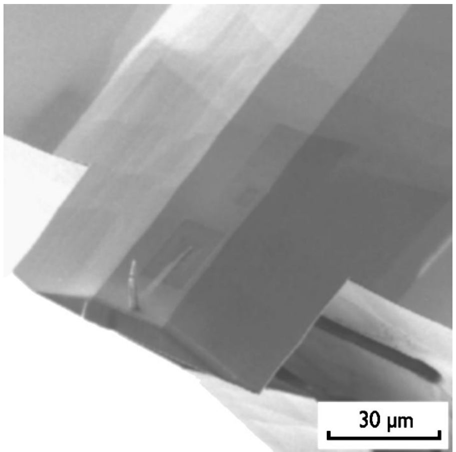

FIG. 2. Scanning ion microscopy image of a cantilever fabricated by cutting a commercially available Si cantilever using an FIB. A carbon tip was deposited at the end of the cantilever using the deposition mode of the FIB.

tions with only small modifications from commercially available DFM setups as discussed below.

There are two major force detection methods in DFM, which are amplitude modulation (AM)[1] and frequency modulation (FM)[6] detection techniques. In AM detection, the cantilever is oscillated at a constant frequency slightly above or below the cantilever resonance with a constant excitation amplitude. Then the tip–sample distance regulation is made by maintaining the cantilever vibration amplitude (A). Thus, AM detection requires the measurement of A. On the other hand, in FM detection, the frequency of the cantilever excitation is continuously tracked at its resonance frequency by using a self-excitation circuit in which the phase (ϕ) of the cantilever vibration is used as a feedback signal. Then the negative or positive shift of the cantilever resonance frequency ($\Delta\omega$) induced by the tip–sample interaction is kept constant for the tip–sample distance regulation. Accordingly, FM detection is based on the measurement of ϕ and $\Delta\omega$. Assuming that the cantilever vibration is described by $A\cos[(\omega_0+\Delta\omega)t+\phi]$, the beat signal contained in the cantilever deflection signal obtained in HOBD method is proportional to $A\cos[(\omega_0+\Delta\omega-\omega_m)t+\phi]$. Therefore, the HOBD method can be applied to each AM and FM detection method by detecting the amplitude, frequency, and phase of the beat signal.

In this experiment, HOBD method is applied to DFM using AM detection method.[1] A commercially available DFM apparatus (JEOL: JSPM-4200) was used with some modifications. An automatic power control (APC) driver (THORLABS: IP-500) and bias-tee (Mini-Circuits: PBTC-1GW) were used for driving a laser diode (Hitachi: HL6312G). rf signals for laser power modulation and cantilever excitation were obtained from the same rf generator (Tektronics: AFG320) so that they are synchronized. The degree of the laser power modulation was about 80%. The bandwidth of the photodetector, which includes position sensitive photodetector, preamplifier, and differential amplifier, was about 600 kHz. The cantilevers used in this experiment were fabricated by cutting commercially available Si cantilevers (Nanosensors: NCL) using a focused ion beam (FIB) as shown in Fig. 2. The length of the cantilever was about 35 μm. The resonance frequency was 5–8 MHz. A carbon tip was deposited at the end of the cantilever using the deposition mode of the FIB.

Figures 3(a) and 3(b) show waveforms of the deflection signal measured with a cantilever having a resonance frequency of about 7 MHz using HOBD method. The frequencies ω_0 and ω_m were 7.0223 and 7 MHz, respectively, so that the frequency of the down-converted beat signal was 22.3 kHz. Figure 3(a) shows the beat signal with a frequency of 22.3 kHz. The waveform is shown as a thick line due to the ω_0 component contained in the deflection signal. The ω_0 component is more clearly recognized in the waveform shown in Fig. 3(b) with smaller time and amplitude scales. Figures 3(c) and 3(d) show FFT spectra of the deflection signal plotted around the beat frequency and vibration frequency, respectively. Since ω_0 (about 7 MHz) is much higher than B (about 600 kHz), ω_0 component in the deflection signal is very small. On the other hand, the beat component is detected with a signal amplitude of 12 times larger than that of ω_0 component. Thus, the signal-to-noise ratio (SNR) of the deflection measurement was improved by using HOBD method instead of traditional OBD method. The result clearly demonstrates that cantilever vibration having a frequency much higher than B can be detected with a sufficient SNR.

Figure 4 shows a DFM image of a Au(111) surface obtained with the same cantilever in air ($\omega_0=7.0223$ MHz and $\omega_m=7$ MHz). The amplitude of the beat signal (22.3 kHz) was used for the distance regulation. The image shows sharp contrast in spite of the fast scanning speed (111 μm/s) and a large corrugation of the surface (about 10 $nm_{p\text{-}p}$), indicating a sufficient time response of the tip–sample distance regulation control. The result reveals that HOBD method enables DFM imaging at cantilever resonance frequencies as high as

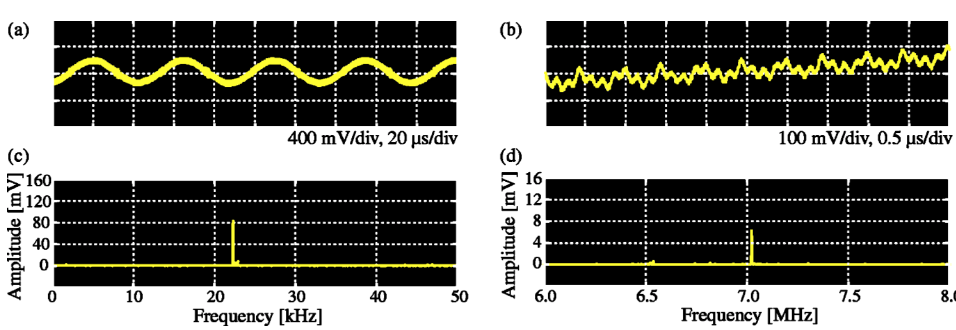

FIG. 3. (Color online): (a) and (b) waveforms of the deflection signal measured with the cantilever vibrating at 7.0223 MHz by HOBD method: (a) shows the down-converted beat signal with a frequency of $\omega_0-\omega_m=22.3$ kHz while (b) shows the ω_0 component (7.0223 MHz) contained in the deflection signal; (c) and (d) FFT spectra of the deflection signal plotted around the beat frequency and vibration frequency, respectively. The spectra show that the signal amplitude of $(\omega_0-\omega_m)$ component was 12 times larger than that of ω_0 component.

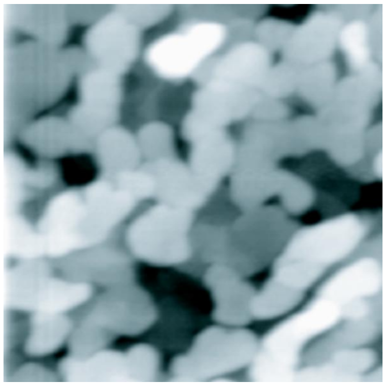

FIG. 4. DFM image of a Au(111) surface obtained by HOBD method in air ($4\ \mu m \times 4\ \mu m$, $\omega_0 = 7.0223$ MHz, $\omega_m = 7$ MHz, tip velocity: 111 $\mu m/s$).

7 MHz even with a conventional photodetector ($B = 600$ kHz). The use of higher resonance frequencies will help us to improve the sensitivity and time response of DFM measurements.

In summary, we have developed a DFM with a wideband cantilever deflection measurement system using HOBD method. Deflection measurement of a cantilever vibrating at about 7 MHz was presented. Using this cantilever, DFM imaging of a Au(111) surface was performed. The result demonstrates that DFM imaging at higher cantilever resonance frequencies is possible even with a conventional photodetector having a much lower bandwidth than a cantilever vibration frequency. HOBD method can be applied to DFM measurements using FM detection method as well as AM detection method. HOBD method also enables surface property measurements using higher order of cantilever resonance frequencies such as KFM[8] and scanning capacitance force microscopy (SCFM).[11]

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